Rice stubble, fertiliser and water management options to reduce nitrous oxide emissions and build soil carbon

by Neil Bull & Terry Rose

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AgriFutures™ Rice

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AgriFutures Australia is the new trading name for Rural Industries Research & Development Corporation (RIRDC), a statutory authority of the Federal Government established by the Primary Industries Research and Development Act 1989.

Foreword

This project aimed to demonstrate on-farm options for temperate Australian rice farmers to lower methane emissions from flooded rice crops by altering water and stubble management, and for subtropical rice growers to use novel slow-release nitrogen fertilisers to reduce nitrous oxide emissions. The project further aimed to demonstrate options to increase soil carbon in temperate flooded rice by modifying stubble management practices.

Emissions of methane and nitrous oxide from Australian rice cultivation systems under current farmer practices were not known, and potential to lower these emissions and enhance soil carbon through changes in farmer practices had not been examined. This project demonstrated how changes in stubble and water management practices could substantially reduce these gas emissions and build soil carbon.

While methane emissions increased when stubble was incorporated rather than being burnt or baled and removed, applying pyrolysed or composted stubble did not increase methane emissions, and applying pyrolysed stubble over three consecutive seasons resulted in increases in soil carbon. One key question as a result of the trials in this project is whether pyrolysing stubble is economically viable, and a full life cycle analysis is required. The trials in this project also focused on rice-on-rice rotations, but given the increase in rice following winter cereal or oilseed crops further studies are needed to resolve baseline emissions and potential mitigation options in these rotational systems.

Current commercially-available nitrogen fertilisers containing nitrification or urease inhibitors do not show any consistent abatement in cumulative seasonal nitrous oxide emissions in rice crops grown in the subtropics. Given that these products have been shown to reduce nitrous oxide emissions by on average 40% elsewhere in the world, steps need to be taken to resolve why they had minimal impact in the warm, humid wet subtropical region of northern NSW and efforts made to develop products that can lower nitrous oxide emissions in these environments.

This project was supported by funding from the Australian Government through the Carbon Farming Initiative, AgriFutures Australia (formerly the Rural Industries Research and Development Corporation), Ricegrowers’ Association of Australia, Rice Research Australia Pty Ltd, NSW Department of Primary Industries and Southern Cross University.

This report for the Rice R&D program is an addition to AgriFutures Australia’s diverse range of over 2000 research publications and it forms part of our Growing Profitability arena, which aims to enhance the profitability and sustainability of our levied rural industries.

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John Harvey
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Southern Cross University – trial management, data interpretation and scientific publications.

New South Wales Department of Primary Industries – greenhouse gas analysis, soil carbon analysis, data analysis and interpretation.

Rice Research Australia Pty Ltd –provision of trial sites, trial management and extension to farmers.

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Executive Summary

What the report is about

This project aimed to demonstrate on-farm options for temperate Australian rice farmers to lower methane emissions from flooded rice crops by altering water and stubble management, and for subtropical rice growers to use novel slow-release nitrogen fertilisers to reduce nitrous oxide emissions. The project further aimed to demonstrate options to increase soil carbon in temperate flooded rice by changing to stubble management practices.

Where are the relevant industries located in Australia?

There are around 1,500 farm businesses growing rice in the temperate climatic zone of the Murrumbidgee Valley, NSW and the Murray Valley of NSW and Victoria. In addition rice is grown in smaller production areas of the sub-tropical Northern Rivers, NSW and tropical zones of Far North Queensland.

Background

Emissions of methane and nitrous oxide from Australian temperate (flooded) and subtropical (aerobic) rice systems under current farmer practices were not known, and potential to lower these emissions and enhance soil carbon through changes in farmer practices had not been examined. This project established a hub site at Rice Research Australia's commercial farm in the Murray Irrigation Area (MIA) to investigate the impact of water management on methane and nitrous oxide emissions from flooded rice crops over three seasons, and to investigate whether changes to stubble management could maintain or reduce methane emissions while increasing soil carbon over three seasons.

Aims/objectives

Emissions of methane and nitrous oxide from Australian rice cultivation systems under current farmer practices were not known, and potential to lower these emissions and enhance soil carbon through changes in farmer practices had not been examined. This project demonstrated how changes in stubble and water management practices could substantially reduce these emissions and build soil carbon.

Methods used

The effect of water management on in-crop methane emissions was investigated over three seasons at a hub site (Rice Research Australia commercial farm) with treatments including full flooding (the traditional system – district practice), drill sowing (crop sown by ground rig with permanent flood water applied 4-5 weeks after sowing) and delayed permanent water (crop sown by ground rig with permanent flood water applied 10-11weeks after sowing). Stubble management effects on in-crop methane emissions and soil carbon were examined in a 3-year trial at the hub site and a one-year trial at a second site with treatments including stubble burnt or removed (district practice) versus novel management options of stubble incorporation, composted stubble or pyrolysed stubble (biochar). Trials at two sites over three seasons in the subtropics investigated the impact of slow-release nitrogen fertilisers (urea vs urea + nitrification inhibitor vs urea + urease inhibitor vs polymer coated urea) on nitrous oxide emissions from soils under rice cultivation. Gas samples and soil samples were taken from replicated trials and analysed for methane/nitrous oxide and soil C fractions, respectively, in an accredited laboratory at NSW DPI Wollongbar. The results of the project were shared with farmers through industry newsletters and presentations at farmer field days and industry research updates, and two draft scientific papers were produced to share the results with the global scientific community.

Results/key findings

Emissions of methane from temperate rice crops under current farmer practices (around 30 g methane/m^2/season) were within the range reported for similar systems across the globe, and methane emissions were the dominant greenhouse gas contributor to global warming potential in these systems, with nitrous oxide emissions making a near negligible contribution. A key outcome of the trials was that drill sowing and delayed permanent water systems in the temperate Australian rice industry can reduce in-crop methane emissions by more than 50 % without significantly increasing nitrous oxide emissions.

Another key outcome was that pyrolysing stubble and re-applying it to soils does not appear to increase methane emissions from rice crops, although the increased nitrous oxide emissions when biochar was added suggest that nitrogen recommendations need to be modified. The addition of pyrolysed rice stubble also resulted in significant increases in soil carbon when applied over three consecutive seasons.

Finally, current commercially available N fertilisers containing nitrification or urease inhibitors do not show any consistent reduction in cumulative seasonal nitrous oxide emissions in rice crops grown in the subtropics.

Implications for relevant stakeholders

Drill sowing of rice crops in the temperate Australian rice industry significantly reduced in-crop methane emissions. Given that drill sowing reduces water use and does not negatively affect grain yields, drill sowing represents a practical option for rice farmers to mitigate methane emissions with no negative impact on crop gross margins.

Pyrolysis of rice stubble appears to be a possible means to reduce stubble burning and the loss of nutrients and carbon from rice soils in the MIA without increasing greenhouse gas emissions; however, a full life cycle analysis needs to be undertaken to determine if such a practice is economically viable.

Given that slow-release nitrogen fertiliser products have been shown to reduce nitrous oxide emissions by an average of 40% elsewhere in the world, steps need to be taken to resolve why they had minimal impact in the warm, humid wet subtropical region of northern NSW and efforts made to develop products that can lower nitrous oxide emissions in these environments.

Recommendations

The proportion of drill sown crops has increased over recent times as a result of commercial drivers such as the potential to lower irrigated water use, a major production input for temperate rice production. A significant amount of crop stubble is often retained at harvest with few cost effective methods available to reduce this residue.

The implications of this research applies to a broad range of rice growing regions and their management systems. As the area of rice grown in tropical conditions increases, we need to identify accurately the factors influencing nitrous oxide emissions from fertiliser application.

Introduction

Emissions of methane and nitrous oxide from Australian temperate (flooded) and subtropical (aerobic) rice systems under current farmer practices were not known, and potential to lower these emissions and enhance soil carbon through changes in farmer practices had not been examined. This project established a hub site at Rice Research Australia's commercial farm in the Murray Irrigation Area (MIA) to investigate the impact of water management on methane and nitrous oxide emissions from flooded rice crops over three seasons, and to investigate whether changes to stubble management could maintain or reduce methane emissions while increasing soil carbon over three seasons. A further satellite site was established in the MIA to investigate stubble management options to build soil carbon without increasing methane emissions. Two sites were also established in the subtropics of Northern NSW to investigate whether changes in nitrogen fertiliser management could reduce nitrous oxide emissions from aerobic rice systems. The outcomes and outputs of the project have established baseline methane and nitrous oxide emissions for temperate (flooded) and subtropical (aerobic) rice systems and have provided rice farmers with management options practices to minimise these emissions and build soil carbon. In addition, data sets were produced that could be used to develop methodologies under Australian Government schemes in the future.

Objectives

This project aimed to demonstrate on-farm options for temperate Australian rice farmers to lower methane emissions from flooded rice crops by altering water and stubble management, and for subtropical rice growers to change nitrogen (N) fertiliser management to reduce nitrous oxide emissions. It further aimed to demonstrate options to increase soil carbon in temperate flooded rice by alterations to stubble management. The effect of water management on in-crop methane emissions was investigated over three seasons at one site with treatments including full flooding (the traditional system – district practice), drill sowing (crop sown by ground rig with permanent flood water applied 4-5 weeks after sowing) and delayed permanent water (crop sown by ground rig with permanent flood water applied 10-11 weeks after sowing). Stubble management effects on in-crop methane emissions and soil carbon were examined in a 3-year trial at one site and a one-year trial at a second site with treatments including stubble burnt or baled and removed (district practice) versus novel management options of stubble incorporation, composted stubble or pyrolysed stubble (biochar). Trials at two sites over three seasons in the subtropics investigated the impact of nitrogen fertiliser formulation (urea vs urea + nitrification inhibitor vs urea + urease inhibitor vs polymer coated urea) on nitrous oxide emissions from soils under rice cultivation. The results of the project were shared with farmers through industry newsletters and presentations at farmer field days and industry research updates, and two draft scientific papers have been produced to share the results with the global scientific community.

Methodology

Field trials were conducted at two commercial farm sites in the Murrumbidgee/Murray Irrigation Area (MIA) and at two commercial farms in the Northern Rivers district of NSW to address the priorities “reducing nitrous oxide emissions’ and ‘increasing carbon stored in soils’.

Trials in the Temperate, flooded rice systems of the MIA were conducted to examine the impact of water management on methane and nitrous oxide emissions and stubble management on methane and nitrous oxide emissions, and soil carbon. Trials in the aerobic, subtropical rice systems of the Northern Rivers were conducted to examine the effect of chemical nitrification inhibitors on nitrous oxide emissions.

Water management to reducing nitrous oxide and methane emissions in flooded rice

Trial design and management

Trials were established over a three-year period at the commercial farm of Rice Research Australia (Jerilderie) to assess the impact of three water treatments (full flooding, drill sowing and delayed permanent water) on methane and nitrous oxide emissions. Full flooding refers to the traditional practice whereby rice bays are flooded prior to aerial sowing of germinated seeds, a system that creates anaerobic soil conditions needed for methane production for most of the season. Drill sowing refers to the process of sowing rice by ground rig and ‘flush’ irrigating the crop for 4 weeks so that the crop is grown aerobically for the first 4 weeks and then is flooded to create anaerobic soil conditions until harvest. Delayed permanent water refers to the practice of sowing rice by ground rig and ‘flush’ irrigating the crop for 9-10 weeks so that the crop is grown aerobically for the first 9-10 weeks and then is flooded to create anaerobic soil conditions from 9-10 weeks after sowing until harvest. During the second season (2014-15), a labour shortage at the farm meant that insufficient measurements were taken to warrant analysis of the data, and as such, only data from the 2013-14 season and the 2015-16 season are presented.

The trial was laid out in a replicated block design in both the 2013-14 and 2015-16 seasons (Figure 1) on adjacent areas of a red brown earth soil (Sodosol). Properties of the 0-100 mm horizon and 100-300mm horizon of the Sodosol in each of the seasons are shown in Table 1. Plots were 4.7m wide x 40m long with a bund height of 600 mm. Crops were managed as per standard district practice and a detailed description of crop management practices for each of the seasons is given in Table 2.

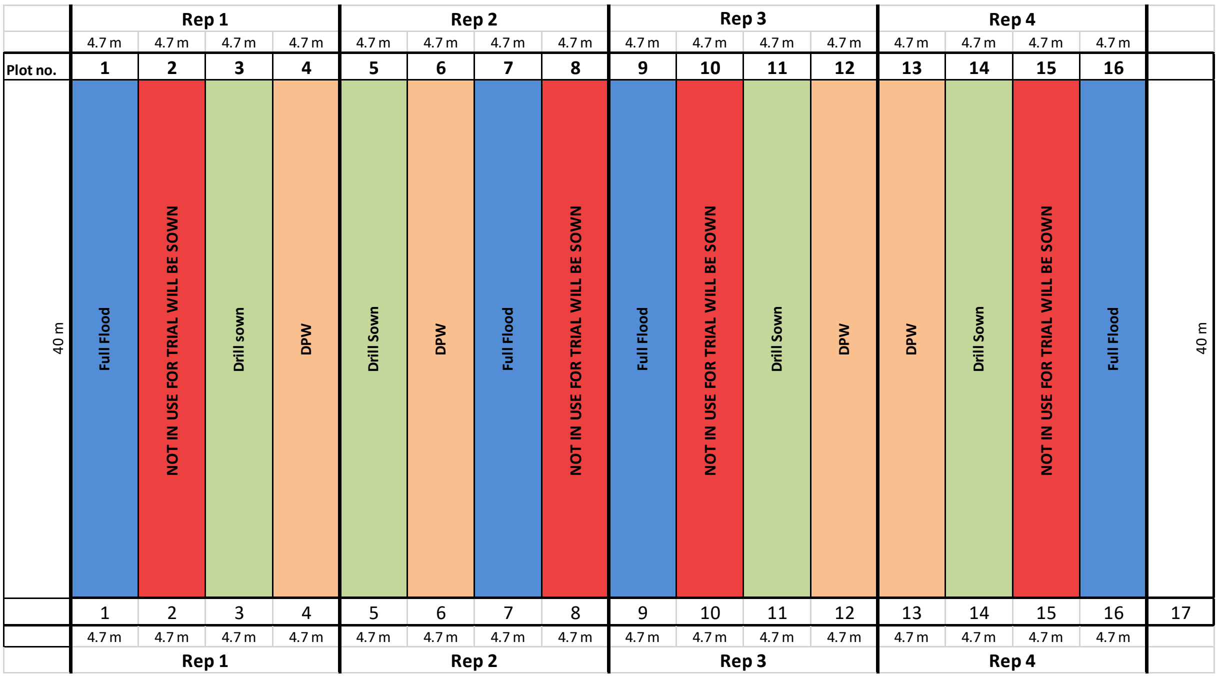


Figure 1. Field layout of water management trial for 2013-14 and 2015-16 seasons

Table 1. Selected physiochemical properties of the 0-100 mm and 100-300 mm horizons of the Sodosol at Jerilderie prior to sowing the 2013-14 and 2015-16 water management trials.

Property	Season and soil depth (mm)			
	2013-14		2015-16	
	0-100 mm	100-300 mm	0-100 mm	100-300 mm
Total carbon (%)	1.5	0.6	1.4	0.6
Total nitrogen (%)	0.1	0.1	0.1	0.1
KCl extractable ammonium (mg kg^{-1})	3.2	1.3	3.0	1.3
KCl extractable nitrate (mg kg^{-1})	14.4	3.0	13.6	3.5
pH (CaCl2)	5.0	6.1	5.0	6.3
EC (dS m^{-1})	0.1	0.1	0.1	0.1
Bray 1 phosphorus (mg kg^{-1})	9.3	2.8	7.4	2.2
Cation exchange capacity (cmol+ kg^{-1})	7.1	14.4	7.4	17.2
Base cations (%)				
Calcium	71.8	44.2	66.4	38.6
Magnesium	19.0	46.2	23.4	50.0
Potassium	5.5	4.1	5.6	3.7
Sodium	2.0	5.4	3.2	7.7
Aluminium	2.7	0	2.5	0

Soil samples were analysed at NSW DPI Wollongbar, Australia, using methods from Rayment and Lyons (2010).

Table 2. Crop management calendar for 2013-14 and 2015-16 trials. CF, DS and DPW refer to conventional flooding, drill sowing and delayed permanent water production systems, respectively.

Management	2013-14 season			2015-16 season		
	CF	DS	DPW	CF	DS	DPW
<u>Land preparation</u>						
stubble burnt	29th Nov 2013	29th Nov 2013	29th Nov 2013	14th Sep 2015	14th Sep 2015	14th Sep 2015
rotary hoeing	30th Nov 2013	30th Nov 2013	30th Nov 2013	17th Sep 2015	17th Sep 2015	17th Sep 2015
<u>Sowing</u>						
date	3rd Dec 2013	1st Dec 2013	1st Dec 2013	13th Nov 2015	23rd Oct 2015	23rd Oct 2015
cultivar	Sherpa	Sherpa	Sherpa	YRM70	YRM70	YRM70
seeding rate	150 kg ha^{-1}	150 kg ha^{-1}	150 kg ha^{-1}	150 kg ha^{-1}	150 kg ha^{-1}	150 kg ha^{-1}
row spacing		200 mm	200 mm		200 mm	200 mm
<u>Fertiliser applied</u>						
MAP drilled 50 mm deep (12 N & 26 P kg ha^{-1})	1st Dec 2013	1st Dec 2013	1st Dec 2013	13th Nov 2015	23rd Oct 2015	23rd Oct 2015
Urea-N drilled 75 mm deep (104 kg N ha^{-1})	1st Dec 2013			13th Nov 2015		
Urea-N Broadcast on soil (104 kg N ha^{-1})		31st Dec 2013				
Urea-N Broadcast on soil (115 kg N ha^{-1})			28th Jan 2014		24th Dec 2015	4th Jan 2016
Urea-N broadcast in water (35 kg N ha^{-1})	28th Jan 2014	28th Jan 2014		14th Jan 2016		
<u>Herbicides</u>						
285 g L^{-1} cyhalofop butyl @ 1 L ha^{-1}	7th Jan 2014	7th Dec 2014				
<u>Water management</u>						
Flush 1		2nd Dec 2013	2nd Dec 2013		2nd Dec 2015	2nd Dec 2015
Flush 2		12th Dec 2013	12th Dec 2013		8th Dec 2015	8th Dec 2015
Flush 3			31st Dec 2013		17th Dec 2015	17th Dec 2015
Flush 4			16th Jan 2014			29th Dec 2015
Permanent water	3rd Dec 2013	31st Dec 2013	28th Jan 2014	13th Nov 2015	24th Dec 2015	4th Jan 2016
Drainage	22nd Apr 2014	25th Apr 2014	25th Apr 2014	30th Mar 2016	30th Mar 2016	30th Mar 2016
<u>Harvest</u>						
Hand cuts	19th May 2014	19th May 2014	19th May 2014	26th Apr 2016	26th Apr 2016	26th Apr 2016
Machine harvest	20th May 2014	20th May 2014	20th May 2014	27th Apr 2016	27th Apr 2016	27th Apr 2016

Quantification of methane and nitrous oxide emissions

Three static chambers were positioned in each plot, approximately 1 m from the edge of the plot to minimise disturbance to plots from gas sampling events. The chambers comprised 300-mm-diameter PVC canisters that were stacked progressively to allow for plant growth as the season progressed. The external surface of all canisters was covered with a reflective foil to minimise the risk of high temperatures inside the chambers (Figure 2). The base canister of each chamber was 300 mm high, of which the bottom 150 mm was inserted into the soil after sowing in the CF plots and after the first flush irrigation event in the DS and DPW plots. Subsequent canisters stacked on top of the base were 400 mm high. At each gas sampling event, a 100-mm-high, 300-mm-diameter chamber lid was fitted to the top canister. The lids contained a magnetic strip on the underside to which a removable battery-operated fan was fitted to ensure mixing of the air inside the chamber during the incubation period (Figure 3). A butyl rubber septum was located 100 mm from the edge of the lid for headspace sampling using a syringe.

Figure 2. Static chambers positioned in plots with external reflective foil to minimise heat buildup within the chamber during the 1.5 hr incubation period

Figure 3. Removable battery-operated fan attached to lids to ensure mixing of the air inside the chamber during the 1.5 hr incubation period

Preliminary testing indicated that saturation of the chambers did not occur with incubation periods of up to 5 h, and linearity was maintained over this period. A 1.5 h incubation period was selected and gas samples were taken immediately after lids were put on (T0) and after 1.5 h (T90), between 0800h and 1100h on sampling days to minimise potential diurnal variation. Gas samples were extracted from the chambers and transferred to pre-evacuated 12-mL Exetainer® vials (Labco, UK) using a 25 mL gas-tight syringe (SGE, 25MDR-LL-GT). Concentrations of methane and nitrous oxide in samples were quantified in an ISO 9001 certified laboratory (NSW Department of Primary Industries, Wollongbar) using an Agilent 7890A gas chromatograph (Agilent Technologies, Santa Clara, USA). A detailed description of gas chromatography analysis and flux conversions is given in Van Zwieten et al. (2010).

In the 2015-16 season, an automated chamber set up was employed using an on-site gas chromatograph housed in an air-conditioned caravan. One automated chamber was positioned in each plot (Figure 4). A detailed description of the automated chamber system can be found in Van Zwieten et al. (2013).

Figure 4. Autochambers used to quantify methane and nitrous oxide emissions in the 2015-16 season

Yield measurements

Biomass cuts at maturity were taken from each plot at dates listed in Table 2 using a 0.5-m-diameter steel ring. Subsequently, a 15m length from all plots was mechanically harvested using a Yanmar GC325 combine harvester with a comb width of 1m. Biomass samples were oven-dried at 60°C for 72 h and weighed, and grain yields from the machine harvest were to 14% moisture basis

Statistical analyses

Biomass and grain yield data were subjected to a two-way ANOVA using water treatment and block as factors using Genstat software (VSN International 2014). Significance of differences between treatment means was tested using a Duncan's multiple range test ($p = 0.05$).

On completion of the trial, statistical analysis of flux data failed to discriminate between (static) chamber positions and so results were presented on a plot average basis. The series of methane and nitrous oxide observations (for static chambers and autochambers) were described by a model that included fixed linear trends over time allowed to vary according to treatment and random effects reflecting the nested design structure due to field replicate, plots within replicates and chambers within plots. Smooth deviations about the linear trends were enabled by inclusion of cubic splines over time. The model was interpolated methane and nitrous oxide emissions on a daily basis and these estimates are presented graphically. Approximate total methane and nitrous oxide emissions from each chamber were calculated by integration under the observed rate curve for each chamber using the trapezoidal rule. Null hypothesis significance tests for equality of average emissions under all treatments were conducted by F-ratio after construction of the nested analysis of variance table. Variance heterogeneity in cumulated methane and nitrous oxide in both years was controlled by transformation to the natural log scale after offset to counter chambers with negative total emissions. The statistical analysis was conducted in the R environment (R core team 2015).

Stubble management to reduce methane emissions and build soil carbon in flooded rice

Trial design and management

Two trials were conducted to assess the effect of stubble management on methane emissions and soil carbon. The first trial was established at the Rice Research Australia commercial farm in the 2013-14 season, and investigated the cumulative effect of removing (baling) stubble (typical farmer practice; treatment 1) to pyrolysing (treatment 2) or composting (treatment 3) stubble for three consecutive seasons (2013-14, 2014-15 and 2015-16) on methane and nitrous oxide emissions and soil carbon. The second trial was conducted at the farm of Troy Mauger in 2014-15 and 2015-16 and compared the impact of stubble removal (baling) with stubble burning, pyrolysed stubble and stubble incorporation on methane and nitrous oxide emissions and soil carbon. During the second season (2014-15), a labour shortage at the Rice Research Australia farm meant that insufficient measurements were taken at the Rice Research Australia farm trial and the trial at Mauger's property to warrant analysis of the data, and as such, only data from the 2013-14 season and the 2015-16 season are presented.

The trial at the Rice Research Australia commercial farm was laid out in a replicated block design in November 2013 (for the 2013-14 season) and treatments were re-applied to the same plots prior to drill sowing of rice in November 2014 (2014-15 season) and in October 2015 (2015-16 season) (Figure 5). Properties of the 0-100 mm horizon and 100-300mm horizon of the Sodosol are shown in Table 3. Plots were 4.7m wide x 40m long with a bund height of 600 mm. Crops were managed as per standard district practice and a detailed description of crop management practices for each of the seasons is given in Table 4.

	Rep 1			Rep 2			Rep 3			Rep 4		
	4.7 m	4.7 m	4.7 m	4.7 m	4.7 m	4.7 m	4.7 m	4.7 m	4.7 m	4.7 m	4.7 m	4.7 m
Plot no.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Treatment	Biochar	Compost	Stubble removed	Compost	Biochar	Stubble removed	Stubble removed	Biochar	Compost	Biochar	Compost	Stubble removed
	1	2	3	4	5	6	7	8	9	10	11	12
	4.7 m	4.7 m	4.7 m	4.7 m	4.7 m	4.7 m	4.7 m	4.7 m	4.7 m	4.7 m	4.7 m	4.7 m
	Rep 1			Rep 2			Rep 3			Rep 4		

Figure 5. Field layout of stubble treatment trial at Rice research Australia farm for 2013-2016

Table 3. Selected physiochemical properties of the 0-100 mm and 100-300 mm horizons of the Sodosol at Rice Research Australia commercial farm prior to sowing the stubble management trial in December 2013 and Mauger's property prior to establishing the stubble management trial in October 2015.

Property	Rice research Australia (December 2013)		Mauger's property (October 2015)	
	0-100 mm	100-300 mm	0-100 mm	100-300 mm
Total carbon (%)	1.1	0.4	1.7	1.1
Total nitrogen (%)	0.1	0.1	0.1	0.1
KCl extractable ammonium (mg kg^{-1})	3.9	2.0	4.7	3.4
KCl extractable nitrate (mg kg^{-1})	7.3	2.3	20	12
pH ($CaCl_2$)	5.6	6.8	4.7	5.4
EC (dS m^{-1})	0.1	0.1	0.1	0.1
Bray 1 phosphorus (mg kg^{-1})	7.0	1.4	11	6.5
Cation exchange capacity (cmol+ kg^{-1})	19	26	7.0	9.8
Base cations (%)				
Calcium	46	39	65	54
Magnesium	48	54	20	38
Potassium	4.1	2.5	8	5
Sodium	2.7	4.3	2	3
Aluminium	0	0	4	0

Soil samples were analysed at NSW DPI Wollongbar, Australia, using methods from Rayment and Lyons (2010).

Biochar for the trial was produced in 2013 by Biochar-Energy Systems (Australia) Pty Ltd using rice straw baled from the 2012-13 rice crop at Rice Research Australia commercial farm, and the same product was used for the trials in 2014-15 and 2015-16 following storage in bulker bags at Rice Research Australia commercial farm. The compost was produced at a neighbouring farm by mixing rice straw with cow manure and composting for 6 months, and the compost product was made each season. The carbon and nitrogen composition of the biochar, compost and straw amendments for each season of the trial are shown in Table 5.

The trial at Troy Mauger's property was laid out in a replicated block design in October 2015 for the 2016-16 trial (Figure 6). As indicated in Figure 6, one entire block (replicate) and small sections of some plots were burnt when the fire for the stubble burnt treatment escaped in October 2015. Owing to this, the trial was continued with only three replicate plots per treatment and the burnt sections of individual plots were not used for any soil carbon, methane and nitrous oxide, or yield assessments. Properties of the 0-100 mm horizon and 100-300mm horizon of the Sodosol are shown in Table 3. Plots were 4.7m wide x 40m long with a bund height of 600 mm. The crop was managed as described in Table 4.

Straw cuts prior to trial establishment indicated that 11.8 t/ha straw was present across the trial, which equated to 4.5 t carbon/ha based on the % carbon of the straw (Table 5). Biochar and compost were applied using a four-wheel motorbike drawn spreader at rates of 56.5 t/ha (wet biochar) and 110 t/ha (wet compost) to match the 4.5 t/ha carbon input as the straw treatment. The straw, biochar and compost were all then incorporated to 10cm depth with a rotary hoe prior to sowing

Table 4. Crop management calendar for stubble trials at Rice Research Australia commercial farm and Mauger's farm

	Rice Research Australia farm			Mauger's farm
Management	**2013-14**	**2014-15**	**2015-16**	**2015-16**
Land preparation				
Stubble baled	29/11/13	02/10/14	11/09/15	14/09/15
stubble burnt	NA	NA	NA	15/09/15
stubble incorporated	NA	NA	NA	15/09/15
Biochar/compost applied	30/11/13	10/10/14	30/10/15	15/09/15
rotary hoeing	30/11/13	10/10/14	30/10/15	15/09/15
Sowing				
date	02/12/13	15/10/14	11/11/15	01/10/15
cultivar	Sherpa	Sherpa	YRM70	Opus
seeding rate	150 kg ha^{-1}	150 kg ha^{-1}	150 kg ha^{-1}	150 kg ha^{-1}
row spacing	200 mm	200 mm	200 mm	200 mm
Fertiliser applied				
MAP drilled 50 mm deep (12 N & 26 P kg ha^{-1})	02/12/13	15/10/14	11/11/15	01/10/15
Urea-N Broadcast on soil (104 kg N ha^{-1})	31/12/13	05/12/14	NA	NA
Urea-N Broadcast on soil (115 kg N ha^{-1})	NA	NA	24/12/15	NA
Urea-N Broadcast on soil (161 kg N ha^{-1})	NA	NA	NA	10/12/15
Urea-N broadcast in water at PI (35 kg N ha^{-1})	28/01/14	NA	NA	NA
Urea-N broadcast in water at PI (69 kg N ha^{-1})	NA	NA	NA	10/01/16
Herbicides				
285 g L^{-1} cyhalofop butyl @ 1 L ha^{-1}	07/01/14			
Water management				
Flush 1	02/12/13	15/10/14	02/12/15	06/11/15
Flush 2	12/12/13	25/10/14	08/12/15	22/11/15
Flush 3	NA	09/11/14	17/12/15	
Flush 4	NA	22/11/14	28/12/15	
Permanent water	31/12/13	05/12/14	07/01/16	10/12/15
Drainage	22/04/14	02/04/15	04/04/16	12/03/16
Harvest				
Hand cuts	19/05/14	05/05/15	26/04/16	13/04/16
Machine harvest	20/05/14	06/05/15	27/04/16	14/04/16

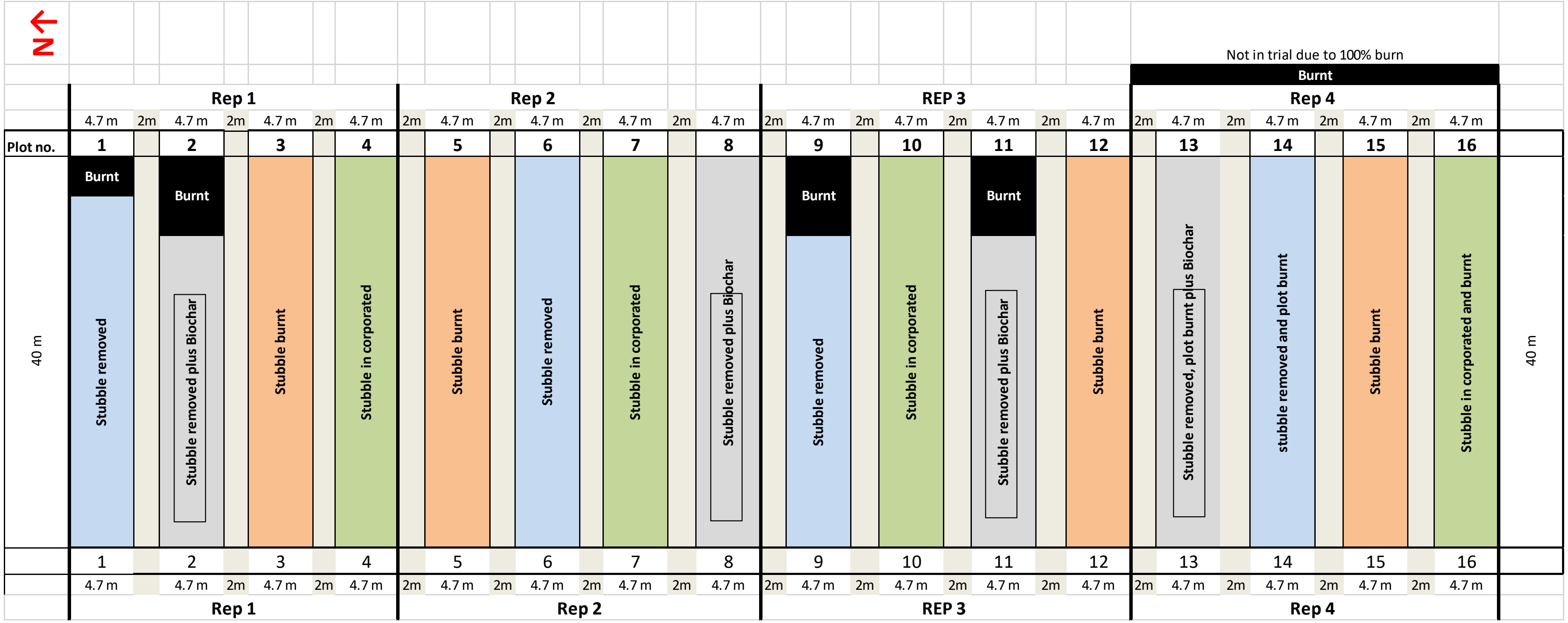


Figure 5. Field layout of stubble management trial at Mauger's property in the 2015-16 season

Table 5. Carbon and nitrogen content of biochar and compost amendments in stubble trials

Amendment property	Rice Research Australia trial			Mauger's trial
season	**2013-14**	**2014-15**	**2015-16**	**2015-16**
Biochar				
Total C (%)	22.6	13	13	13
Total N (%)	1.69	0.66	0.61	0.61
C:N ratio	13.4	16.6	21.3	21.3
% moisture	38	35	45	45
Compost				
Total C (%)	11.7	9.3	4.9	4.9
Total N (%)	0.91	0.55	0.34	0.34
C:N ratio	12.8	16.9	14.4	14.4
% moisture	33	28	17	17
Straw	NA	NA	NA	
Total C (%)				42.4
Total N (%)				0.85
C:N ratio				49.6
% moisture				10

Yield measurements

Biomass cuts at maturity were taken from each plot at dates listed in Table 4 using a 0.5-m-diameter steel ring. Subsequently, a 15m length from all plots was mechanically harvested using a Yanmar GC325 combine harvester with a comb width of 1m. Biomass samples were oven-dried at 60°C for 72 h and weighed, and grain yields from the machine harvest were to 14% moisture basis.

Soil carbon measurement

Soil samples (0-100mm and 100-300mm depths) were taken from each plot at Rice Research Australia commercial farm and Mauger trial sites prior to amendment addition using SCaRP protocols (Baldock *et. al*., 2013). Further soil samples were taken (as per SCaRP protocols) after the harvest of the crop in the first season at Rice Research Australia commercial farm (about 6 months after amendment addition) and at the completion of the 2015-16 trial at Mauger's property (about 6 months after amendment addition). Samples were also taken from the Rice Research Australia commercial farm trial after the third consecutive season (June 2016, around 30 months after the amendments were first applied). Total carbon was assessed at each sampling occasion at the NATA accredited laboratory at NSW DPI, Wollongbar, as per the KPIs for Milestones 3-8. Fractionation of carbon into recalcitrant organic carbon (ROC), particulate organic carbon (POC), total organic carbon (TOC) and humus (HUM) was undertaken at NSW DPI laboratories at Wollongbar, NSW, using MIR as per Baldock et al. (2013).

Statistical analyses

For each trial site, soil data were analysed as a two-way analysis of variance using amendment and block as the treatments factors in Genstat. All methane and nitrous oxide emissions data were analysed as per the data from the water management trials.

Mitigating nitrous oxide emissions in subtropical rice using nitrification inhibitors

Trial design and management

Two trials were conducted in each of the 2013-14, 2014-15 and 2015-16 seasons in the subtropics to assess whether nitrification inhibitors, urease inhibitors or polymer coating could lower nitrous oxide emissions from soils amended with urea. Trials were conducted each year on a clay soil (Hydrosol) near Woodburn (Carusi's farm) and a peat soil (Organosol) near Lismore (Woolley's farm). Selected properties of the soils used in each year are given in Table 6.

Table 6. Selected physiochemical properties of the 0-100 mm horizon of the Hydrosols and Organosols in the nitrous oxide mitigation trials in the subtropics.

Property	Hydrosol			Organosol	
Season	2013-14	2014-15	2015-16	2013-14	2015-16
Total carbon (%)	4.0	2.3	4.3	6.8	7.7
Total nitrogen (%)	0.3	0.2	0.3	0.6	0.6
KCl extractable ammonium (mg kg^{-1})	6.4	9.9	4.9	9.0	5.2
KCl extractable nitrate (mg kg^{-1})	35	0.9	6.3	86	3.1
pH ($CaCl_2$)	6.0	5.6	5.5	4.8	4.9
EC (dS m^{-1})	0.2	0.0	0.1	0.3	0.1
Bray 1 phosphorus (mg kg^{-1})	8.0	15	10	10	15
CEC (cmol+ kg^{-1})	32	27	26	15	14
Base cations (%)					
Calcium	48	54	40	39	17
Magnesium	44	37	50	22	12
Potassium	6	2	2	4	1
Sodium	6	1	5	4	3
Aluminium	0	3	2	28	43

Soil samples were analysed at NSW DPI Wollongbar, Australia, using methods from Rayment and Lyons (2010).

2013-14 season

Trials were established at both sites with three N fertiliser treatments: urea, urea + the nitrification inhibitor DMPP (a commercial product named entec®) and a 50:50 blend of urea and entec®. All N treatments were applied at 90 kg N/ha and trials were established in a randomised block design with four replicates. Fertilisers were applied to the main plots by hand (broadcast) and at Carusi's farm were then incorporated by farmer machinery. Crop management is detailed in Table 7

2014-15 season

Trials were established at both sites with three N fertiliser treatments: urea, entec® and polymer coated urea. All N treatments were applied at 90 kg N/ha and trials were established in a randomised block design with four replicates. Fertiliser were applied to the main plots by hand (broadcast). In the trial on the Organosol, the rice crop was destroyed by cane grubs soon after rice emergence and the trial was abandoned, so only data from the Hydrosol are presented in the discussion section. Crop management is detailed in Table 7.

2015-16 season

Owing to the abandonment of the previous season's trial on the Organosol, an additional two products were trialed at both sites in the 2015-16 season. Trials were established at both sites with five N fertiliser treatments: urea, entec®, urea + the urease inhibitor NBPT (a commercial product named green urea®), polymer coated urea and urea + carbon (a commercial product named black urea®). All N treatments were applied at 90 kg N/ha and trials were established in a randomised block design with four replicates. Fertiliser were applied to the main plots by hand (broadcast) and at Carusi's farm were then incorporated by farmer machinery. Crop management is detailed in Table 7.

Yield measurements

At maturity at Carusi's property in the 2013-14 and 2014-15 seasons, 2 m of row was cut from two separate areas of each plot by severing plants about 10 mm from the soil surface. Grain was manually threshed from straw and grain/straw tissue was dried at 40 C for 7 d before being weighed. Grain yields were converted to a 14% moisture basis.

At Woolley's property in 2013-14, a cold weather event in March led to grain sterility and no grain formed in any N treatment. Biomass cuts were taken from 2 m of row from two separate areas of each plot prior to the crop being baled for hay using commercial equipment.

In the 2015-16 season at both sites, an 8 m length of plots was harvested with a Wintersteiger small plot harvester with a 1 m comb width. Grain yields were expressed on a per ha basis at 14% moisture (industry standard).

Quantification of methane and nitrous oxide emissions

Three 150-mm-diameter manual static chambers, as described in Van Zwieten et al. (2013), were placed randomly in each plot. Chambers were closed then sampled immediately and then resampled after a 1 h incubation period. Preliminary testing that indicated no saturation of the chambers occurred within the 1 h incubation period. On completion of the trial, statistical analysis of flux data failed to discriminate between chamber positions and so results were presented on a plot average basis. All other statistical analyses for gas emissions were conducted as described earlier for the methane emissions in the water management trial.

Statistical analyses

All statistical analyses were conducted as per the data from the water management trials.

Table 7 - Crop management calendar for nitrous oxide emission trials in the subtropics

		Carusi's property			Woolley's property	
Crop management		**2013-14**	**2014-15**	**2015-16**	**2013-14**	**2015-16**
Previous crop		Sugarcane	Sugarcane	Sugarcane	Rice	Rice
Land preparation						
	discing	15/12/13	18/11/14	20/11/15	15/01/14	12/12/15
	rotary hoeing	06/01/14	06/12/14	07/12/15	NA	NA
	power harrowing	06/01/14	06/12/14	09/12/15	23/01/14	20/12/15
Rice sown						
	date	07/01/14	07/12/14	10/12/15	24/01/14	27/12/15
	cultivar	Tachiminori	Tachiminori	Doongara	Langi	Langi
	seeding rate	125 kg ha^{-1}	125 kg ha^{-1}	125 kg ha^{-1}	120 kg ha^{-1}	120 kg ha^{-1}
	row spacing	150 mm	150 mm	150 mm	200 mm	200 mm
Fertiliser applied						
	Drilled phosphorus (20 kg ha^{-1})	07/01/14	07/12/14	NA	NA	NA
	Broadcast nitrogen (90 kg ha^{-1})	06/01/14	21/01/15	09/12/15	25/02/14	09/02/16
Herbicides						
	480 g L^{-1} Clomazone @ 600 mL ha^{-1}	07/01/14	07/12/14	09/12/15	24/01/14	27/12/15
	480 g L^{-1} Propanil @ 8 L ha^{-1}	NA	NA	NA	12/02/14	NA
Harvest		10/05/14	21/04/15	10/05/16	15/05/14	31/05/16

Discussion

Outcome 1: Reduced methane emissions from flooded rice systems

Trials at Rice Research Australia commercial farm and Mauger's farm in the MIA investigated the effect of water management and stubble management on in-crop methane emissions and crop yields.

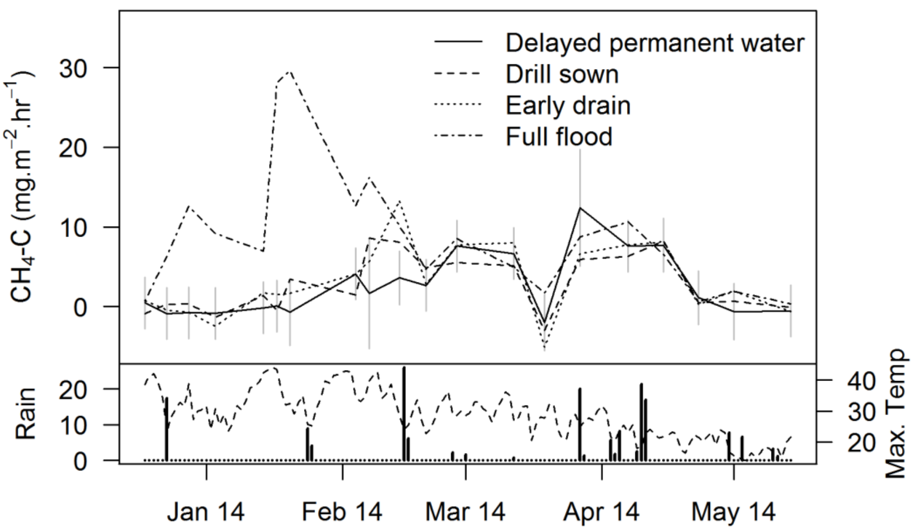
Water management to reduce methane emissions in flooded rice systems

In both the 2013-14 season and the 2015-16 season, the drill sowing and delayed permanent water treatments had significantly lower methane emissions during the first 3 months after sowing (Figure 6 a, b, c).

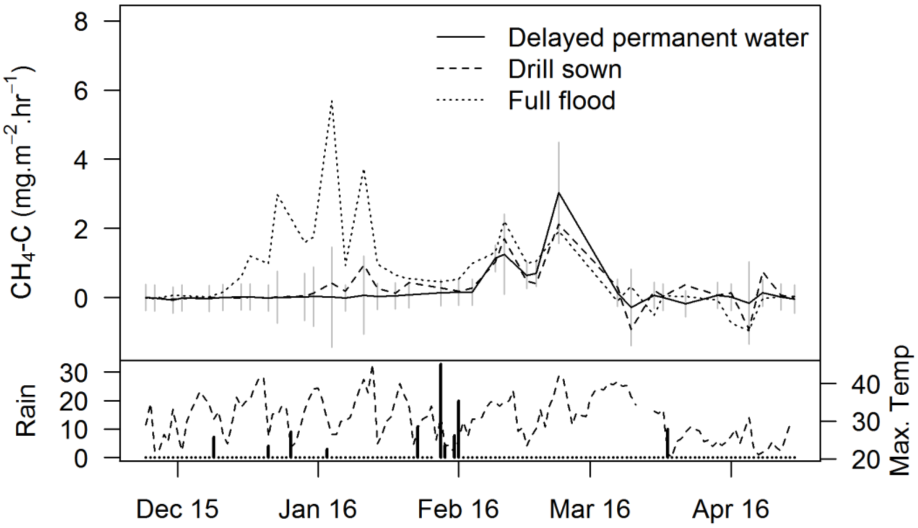
During the latter half of the season there was no significant difference in methane fluxes among the treatments. While no measurements of carbon dioxide were taken (because plants were present within the static chambers), presumably the labile carbon in soils that was emitted as methane during the first two months under the full flooding treatment (anaerobic soil conditions) was emitted as carbon dioxide in the first two months under the aerobic drill sown treatments.

Cumulative in-crop methane emissions were significantly lower (around half) in the drill sown and delayed permanent water treatments compared to the full flooding treatment in both seasons (Table 8). In the 2013-14 season, however, the drill sowing and delayed permanent water treatments resulted in a grain yield penalty of around 5t/ha (Table 8), which we attribute to the extremely late sowing of the trial in December 2013 (compared to an optimum October or early November sowing date) which has a greater impact on drill sown crops. The fact that no yield differences were observed between treatments in the 2015-16 season when drill sown crops were sown on 23rd October suggest that the yield penalty was an anomaly caused by the late sowing date rather than an inherent yield penalty in drill sowing systems. This is supported by numerous trials indicating that drill sowing does not incur a yield penalty compared to full flooding (Dunn et al. 2015).

a) 2013-14 season



b) 2015-16 season



c) 2015-16 season, autochambers

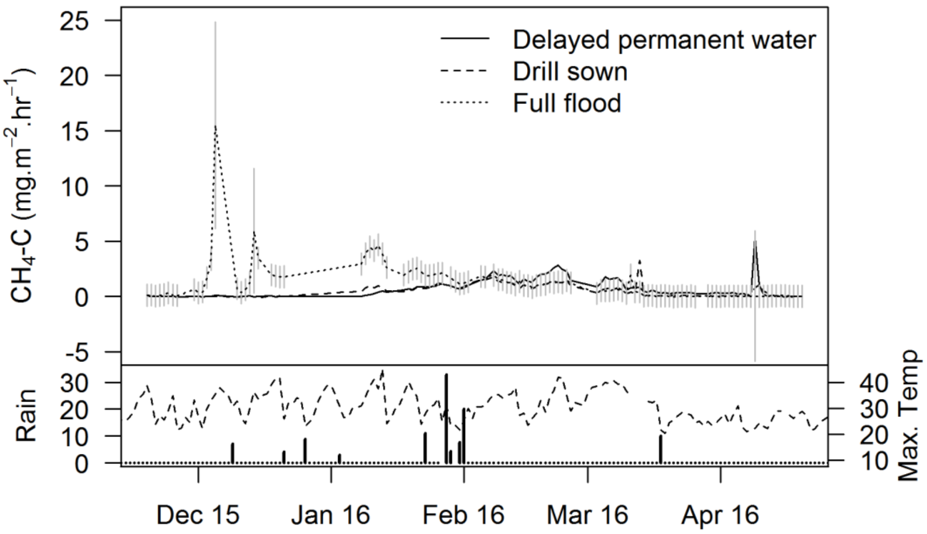


Figure 6. In-crop methane fluxes at the Rice Research Australia trial sites in a) 2013-14 and b) 2015-16. Vertical bars represent twice the standard deviation from the delayed permanent water treatment.

Table 8. Grain yields and cumulative methane and nitrous oxide emissions under full flooding, drill sown or delayed permanent water irrigation regimes in the 2013-14 and 2015-6 seasons. Means within a column for each season that do not share a common letter are significantly different at P = 0.05.

Water treatment	Methane flux per season (g/m^2)	Nitrous oxide flux per Season (mg/m^2)	Grain yield (t/ha)
2013-14			
Full flooding	29.3 a		14.0 a
Drill sowing	11.8 b	ns*	9.0 b
Delayed permanent water	9.7 b		9.7 b
mean		36.6	
2015-16			
CF	28.1 a		
DS	11.2 b	ns*	ns*
DPW	10.1 b		
Mean		0.23	9.7
2015-16 Autochamber			
CF	54.9 a		
DS	16.6 b		
DPW	22.9 b		

*ns denotes no significant difference among means at P = 0.05

Cumulative seasonal nitrous oxide emissions were around a thousand times lower than seasonal methane emissions (Table 8), confirming that methane is the dominant contributor to greenhouse gas emissions from flooded rice soils. Unlike the results from many overseas studies, our trials did not show any increase in cumulative nitrous oxide emissions as a result of the drill sowing or delayed permanent water regimes (Table 8), which is likely due to the fact that nitrogen fertiliser was applied immediately prior to permanent flooding in the drill sown and delayed permanent water systems, and the anoxic conditions following flooding of soils are not conducive to nitrous oxide formation.

Interestingly, while the delayed permanent water treatment had a 4-5 week longer anaerobic phase than the drill sown treatment, this did not result in further lowering of methane emissions. While the delayed permanent water regime uses less water than the drill sowing system (which in turn uses less water than the full flooding system), the longer delay in flooding the rice crops is detrimental for populations of the Australian Bittern, which relies on ponded water in the region during this time. Thus, the drill sowing system may provide a compromise that significantly lowers methane emissions but still provides a habitat for bitterns at the critical time of the year.

Stubble management to reduce methane emissions from flooded rice systems

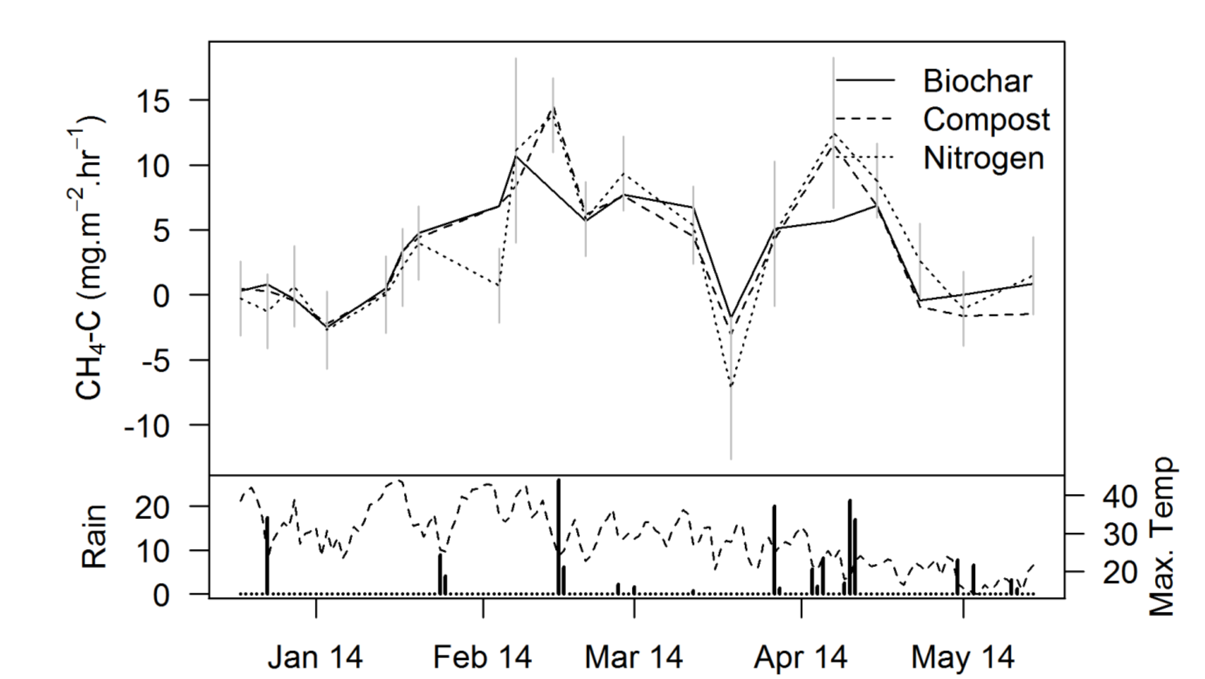
In the trial at Rice Research Australia commercial farm, where stubble management treatments were repeated on the same plots over three consecutive seasons, seasonal methane emissions were < 30 g/m^2 (Table 9), reflecting the fact that the trials were drill sown each season and much of the labile carbon in soil was likely emitted as carbon dioxide during the aerobic growth phase prior to permanent flooding. Despite the compost and biochar treatments providing N to the soil prior to sowing (present during the 4-week aerobic growth phase following drill sowing in each season), these treatments did not significantly increase nitrous oxide fluxes during the aerobic phase in the 2013-14 or 2015-16 season (Figure 8a, b) and did not significantly increase cumulative nitrous oxide emissions in either season (Table 9).

Grain yields did not differ among stubble treatments in any season, but yields were lower than district average (around 10t/ha) in the first two seasons. Yields were likely low (around 4t/ha) in the 2013-14 season because of the late sowing (as per the water management trial in this season), while in the 2014-15 season the grain yields were low (around 5 t/ha) because of cold-induced floret sterility. However, early sowing and warmer temperatures during the reproductive growth phases in the 2015-16 season led to a higher mean yield of around 9t/ha.

Table 9. Grain yields and cumulative methane and nitrous oxide emissions at the Rice Research Australia commercial farm stubble management trial across three consecutive seasons. Means within a column for each season that do not share a common letter are significantly different at P = 0.05.

Stubble treatment	Methane flux per season (g/m^2)	Nitrous oxide flux per Season (mg/m^2)	Grain yield (t/ha)
2013-14			
Stubble removed	12.8		
Stubble removed + biochar	13.7	ns*	ns*
Stubble removed + compost	13.9		
mean		6.7	4.17
2014-15			
Stubble removed	NA	NA	
Stubble removed + biochar	NA	NA	ns*
Stubble removed + compost	NA	NA	
mean			5.23
2015-16			
Stubble removed	3.8		
Stubble removed + biochar	4.1	ns*	ns*
Stubble removed + compost	3.5		
mean		4.5	9.06

a) 2013-14 season



b) 2015-16 season

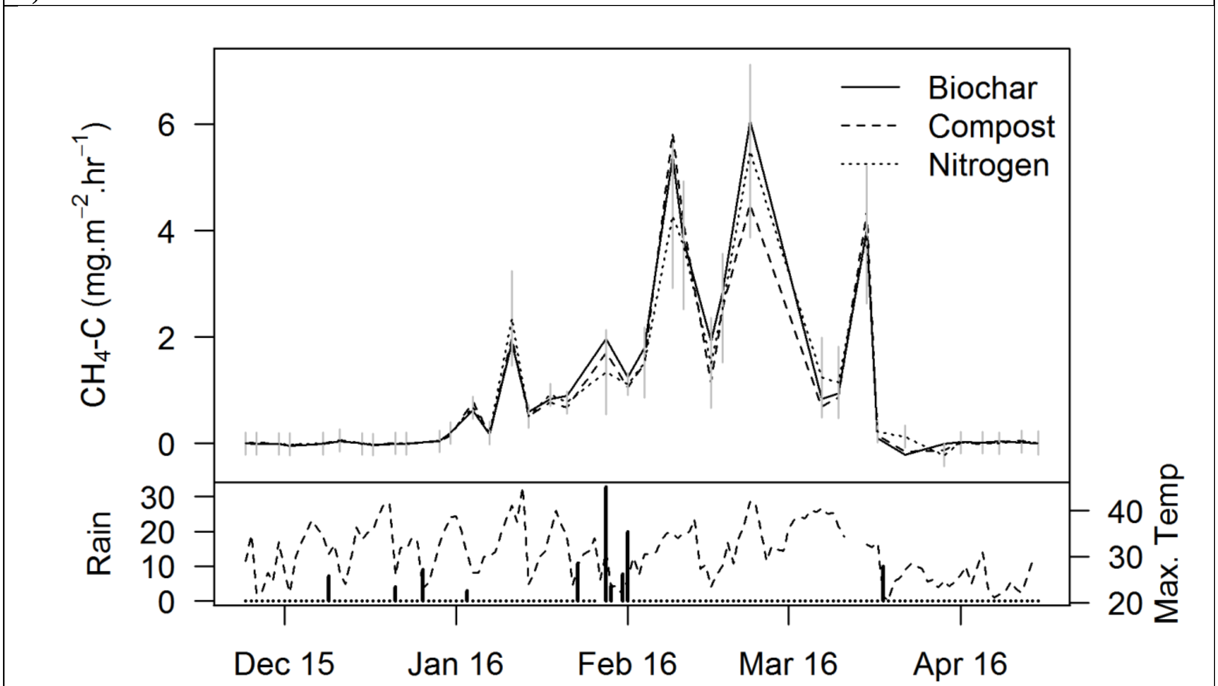
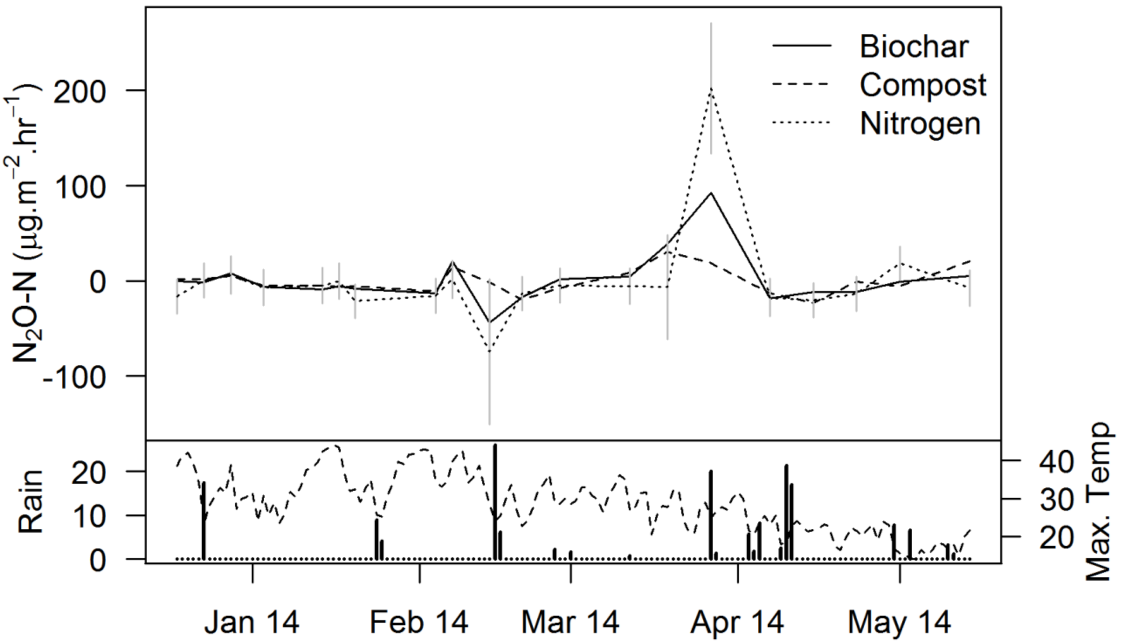


Figure 7. **In-crop methane fluxes at the Rice Research Australia commercial farm stubble management trial in a) 2013-14 and b) 2015-16. Vertical bars represent twice the standard deviation from the nitrogen fertiliser treatment.**

a) 2013-14 season



b) 2015-16 season

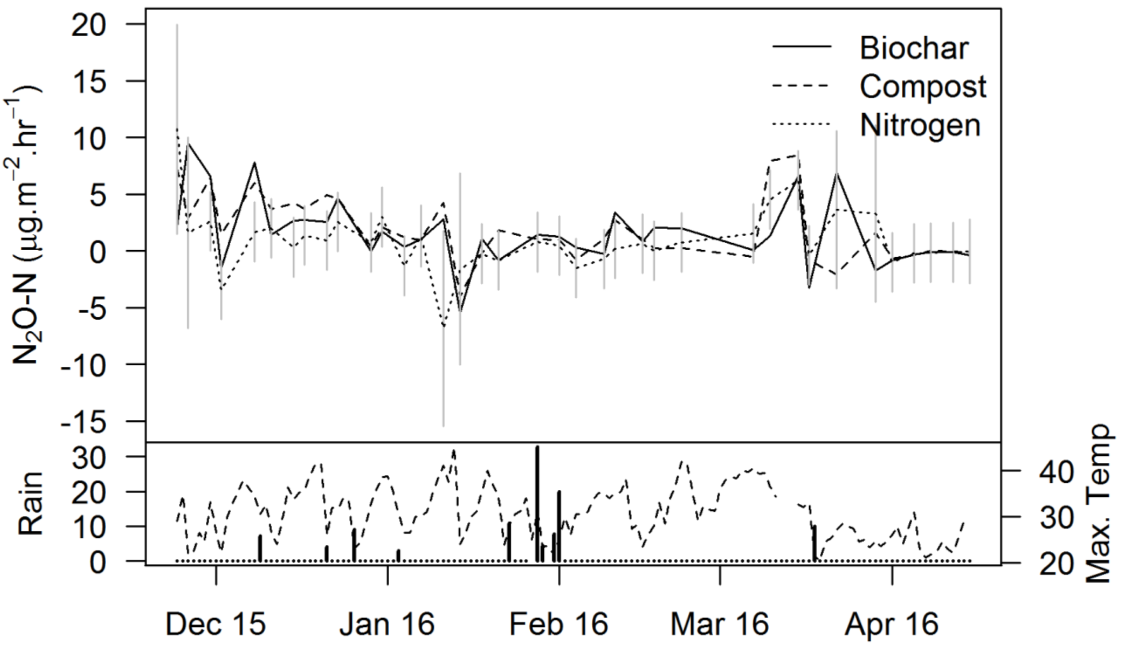


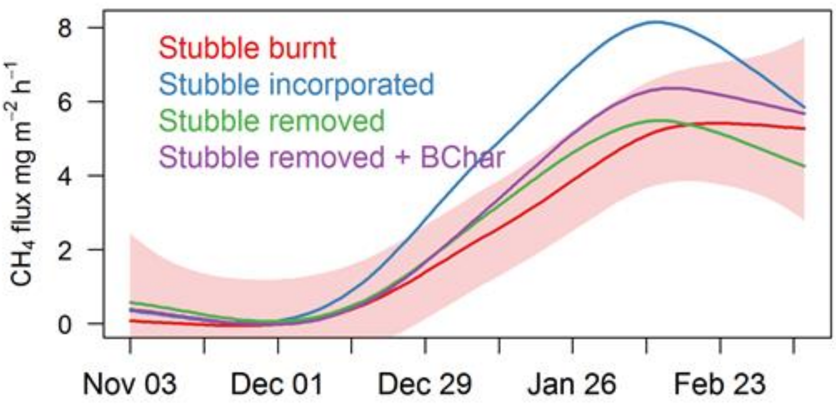
Figure 8. **In-crop nitrous oxide fluxes at the Rice Research Australia commercial farm stubble management trial in a) 2013-14 and b) 2015-16. Vertical bars represent twice the standard deviation from the Nitrogen (stubble removed) treatment.**

Methane fluxes were significantly greater in the stubble incorporated treatment during the first 3 months than the three other treatments (stubble removed, stubble burnt and stubble removed + biochar) (Figure 9a), resulting in significantly higher cumulative methane emissions across the season (Table 10). However, presumably a proportion of the carbon added as straw in the stubble incorporated treatment was emitted as carbon dioxide during the 6-week aerobic phase following sowing. We suggest that the differences in cumulative methane emissions between the stubble incorporated treatment and the other three treatments would have been substantially greater had the crop been grown under full flooded conditions. Nitrous oxide fluxes were only substantial during the first month after sowing, and were significantly greater in the biochar treatment than all other treatments during this time.

Consistent with the Rice Research Australia commercial farm trial, the addition of biochar (at 4.5 t carbon/ha) did not significantly increase cumulative methane emissions compared to the stubble burnt and stubble removed treatments (Table 10). It therefore appears that the carbon present in biochar is somewhat recalcitrant and resistant to degradation by microbes under anaerobic conditions. Thus, the conversion of stubble biomass into biochar appears to be an option to minimise removal of carbon and nutrients from paddocks without increasing methane emissions. However, cumulative nitrous oxide emissions were significantly higher in the biochar treatment than the stubble incorporated or stubble bunt treatments, reflecting the larger N inputs into the system in the biochar treatment. While ultimately the nitrous oxide emissions are orders of magnitude lower than methane emissions so the biochar treatment still mitigates greenhouse gas emissions compared to the stubble incorporated treatment, further research to optimise (reduce) the N fertiliser inputs where biochar is added may lead to lowering of nitrous oxide emissions from paddocks where biochar is added as an amendment.

In the stubble management trial at Mauger's property in the 2015-16 season, grain yields were higher in the biochar treatment than all other treatments (Table 10). The reason for this is not known but we hypothesise that is was a result of nutrient addition in the biochar that overcame a nutrient limitation in that paddock.

a) Methane



b) Nitrous oxide

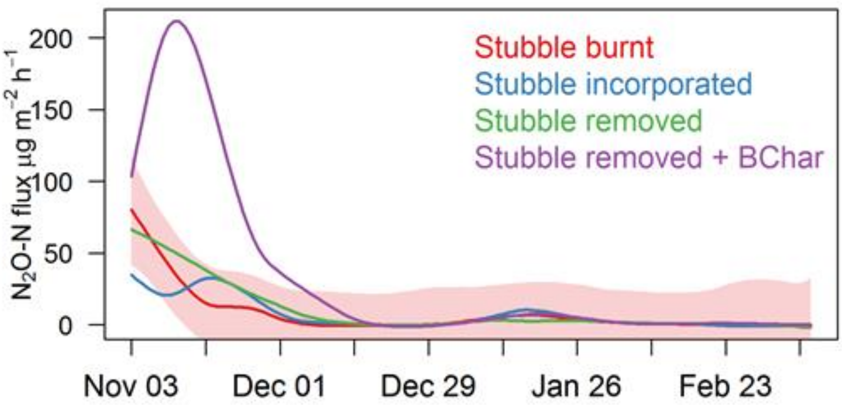


Figure 9. In-crop methane (a) and nitrous oxide (b) fluxes at the Mauger stubble management trial in 2015-16. Pink shading represents twice the standard deviation from the stubble removed treatment.

Table 10. Grain yields and cumulative methane and nitrous oxide emissions at the 2015-16 season stubble management trial at Mauger's property. Means within a season that are not followed by a common letter are not significantly different at P = 0.05.

Stubble treatment	Methane flux per season (g/m^2)	Nitrous oxide flux per Season (mg/m^2)	Grain yield (t/ha)
Stubble removed	79 a	0.35 ab	6.89 a
Stubble burnt	73 a	0.25 a	7.66 a
Stubble incorporated	115 b	0.25 a	7.94 a
Stubble removed + biochar	89 a	1.06 b	9.22 b

Outcome 2: Reduced nitrous oxide emissions from subtropical rice soils

Crop yields

The mean rice grain yields (14 % moisture) at the 2013-14, 2014-15 and 2015-16 Carusi trial sites were 6.2 t/ha, 5.7 t/ha and 6.9 t/ha, respectively, and were not affected by N fertiliser treatment in any season. At site at Woolley's property in 2013-14, a cold weather event in March led to grain sterility and no grain formed in any treatment. Mean aboveground crop biomass was 15.2 t/ha, with no significant effect of N fertiliser treatment. In the 2015-16 season, grain yields at the Woolley site did not differ among N treatments (mean = 5.2 t/ha). That yields were not affected by any of the novel N fertilisers is not surprising given that the control treatment (urea) was applied at rates that already achieve maximum N-limited grain yields in the region. Put simply, the trials were designed to assess nitrous oxide emissions at one N application rate rather than to determine the optimum application rate for each of the novel N fertiliser products.

Nitrous oxide emissions

Carusi field site

At the Carusi 2013-14 trial, during the peak flux event in late January following a 30 mm rainfall event, nitrous oxide emissions were significantly lower in the urea-DMPP and blend treatments than in the urea treatment ($P < 0.05$; Fig. 10A). Beyond this flux event, however, nitrous oxide fluxes in all treatments were negligible despite rainfall events > 50 mm in late March and April. In the 2014-15 season, nitrous oxide fluxes in the polymer coated urea treatment were lower than the urea treatment during the peak flux event but this was only significant at $P < 0.1$ (Fig. 10B). Ultimately, cumulative nitrous oxide emissions did not differ among treatments in the 2013-14 or the 2014-15 season at Carusi's property (Table 11) and this lack of any significant difference in cumulative nitrous oxide emissions among N fertiliser treatments was observed at all sites and seasons in the subtropics (Table 11). In fact, other than the 2013-14 Carusi trial, the novel N fertilisers did not even significantly ($P < 0.05$) lower nitrous oxide emissions during peak flux events, and flux data from the 2013-14 Woolley trial and both 2015-16 trials are therefore not shown.

In the 2015-16 season at the Carusi site, nitrous oxide emissions with urea were compared to emissions from a range of enhanced efficiency N fertiliser products including urea-DMPP (Entec), urea-NBPT (Green urea, which contains a urease inhibitor), polymer coated urea and black urea (a commercially available carbon-based urea product) and brown coal-urea (a research pilot carbon-based urea product). A nil N control treatment was also included. There was no significant difference in soil nitrous oxide emissions at any flux events (Fig. 11), and ultimately there was no significant difference in cumulative seasonal emissions among N fertiliser products. There was a difference in cumulative emissions between the nil-N treatment and all N fertiliser treatments except polymer coated urea at P= 0.13, however.

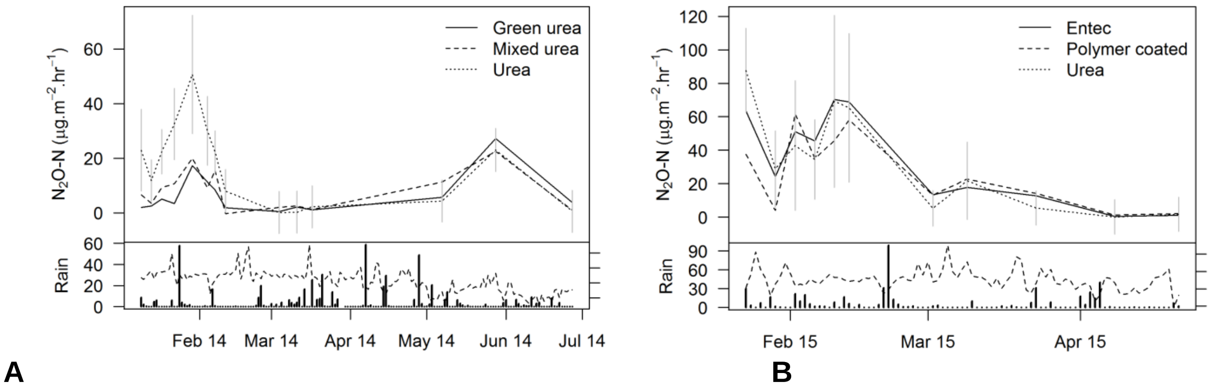


Figure 10. Nitrous oxide emissions at Carusi's property in a) 2013-14 and b) 2014-15 under three N fertiliser treatments. Vertical bars represent twice the standard deviation from the urea treatment.

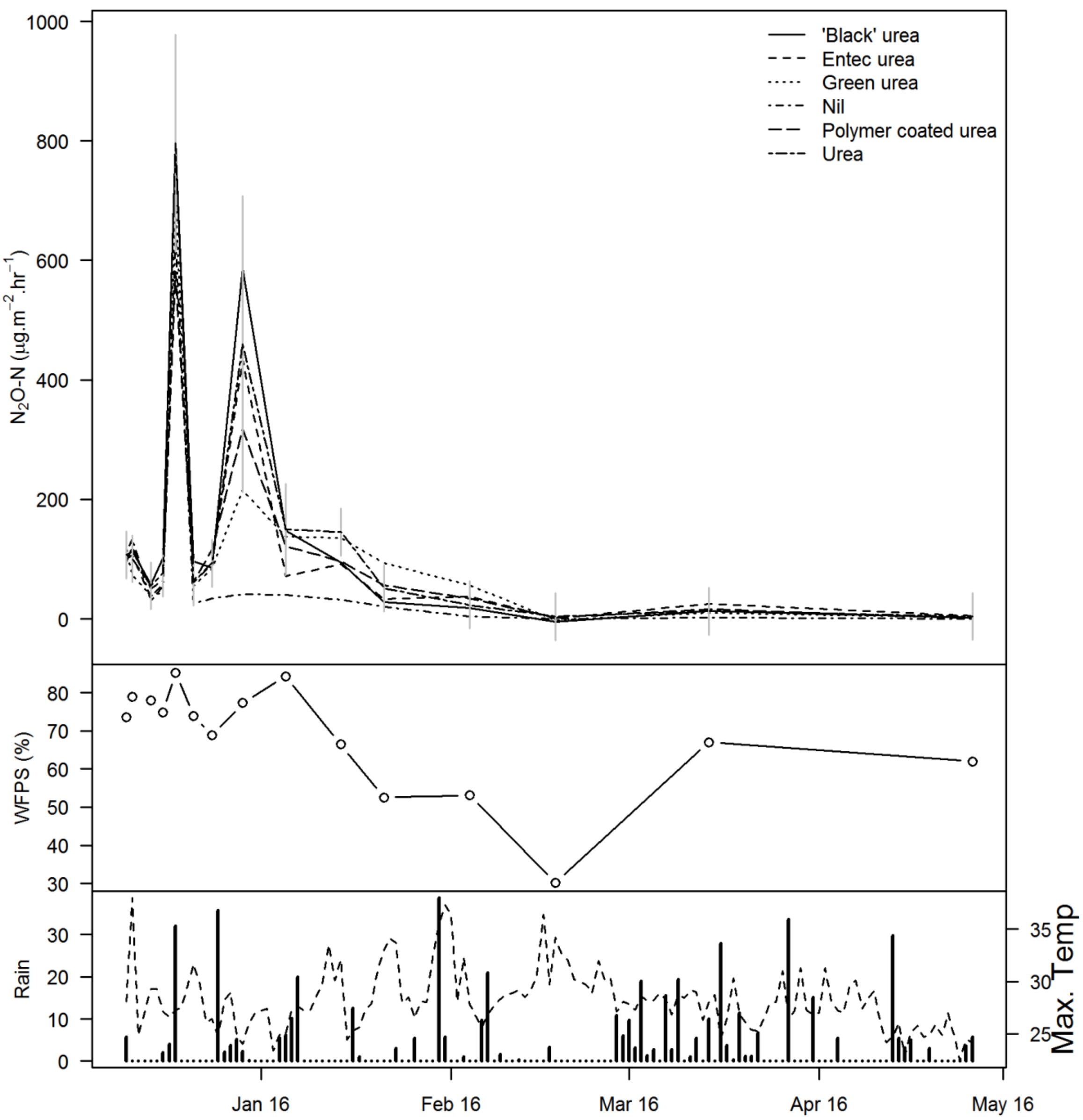


Figure 11. Nitrous oxide emissions (observations) under seven N fertiliser treatments at Carusi's property in 2015-16. The second panel depicts Water Filled Pore Space (WFPS) in the soil. The lower panel shows weather observations.

Table 11. Cumulative nitrous oxide emissions in aerobic subtropical rice paddocks with urea vs novel N fertilisers. A 'P' value > 0.05 indicates the means within that column are not significantly different at P = 0.05.

	Cumulative seasonal nitrous oxide-N emissions (kg N/ha)			
N treatment	Woolley 2015-16	Carusi 2013-14	Carusi 2014-15	Carusi 2015-16
Urea	0.06	0.42	0.41	2.24
Urea-DMPP**	0.04	0.30	0.45	1.97
Split	NA	0.34	NA	NA
PCU	0.05	NA	0.38	1.79
Urea-NBPT***	0.07	NA	NA	1.92
Urea-BLcarbon****	0.04	NA	NA	2.24
Nil-N	0.04	NA	NA	0.83
mean		0.35	0.41	
SE	0.01	0.09	0.16	0.33
lsd	0.02	0.34	0.21	1.01
P	0.15	0.68	0.73	0.13

* NA: not measured at that trial site

** Urea-DMPP is sold commercially as Entec™

***Urea-NBPT is sold commercially as Green Urea™

****Urea-BLcarbon is sold commercially as Black Urea™

Wooley field site

A field trial was carried out on a peat soil at the Wooley trial site in 2015-16 comparing urea with five other enhanced efficiency N fertiliser products and a nil-N treatment, as per the Carusi 2015-16 trial. Fluxes of nitrous oxide were particularly low at this site under all treatments, with peak nitrous oxide fluxes around 100 times lower than those at the Carusi site in the same season (Fig. 12). Ultimately, there was no significant difference in cumulative seasonal nitrous oxide emissions among any N fertiliser treatments, and total emissions were over 10 times lower than at the Carusi site (Table 11).

A recent meta-analysis study indicated that globally enhanced efficiency N fertiliser products reduce nitrous oxide emissions by around 40% across studies (Akiyama et al. 2010), raising questions as to why the products were ineffective in our studies. Closer examination of the studies used in the meta-analysis of Akiyama et al. (2010) indicates that most of the studies were from temperate regions, and further literature searches indicated there is little data available for tropical and subtropical regions. We therefore suggest that the lack of significant mitigation of nitrous oxide emissions from these novel fertilisers in this project was due to the warm and wet conditions of the NSW subtropical rice growing region. Further studies are needed to elucidate why these N fertiliser products are ineffective under such conditions and to identify means by which to improve these products or to determine what types of products may be effective.

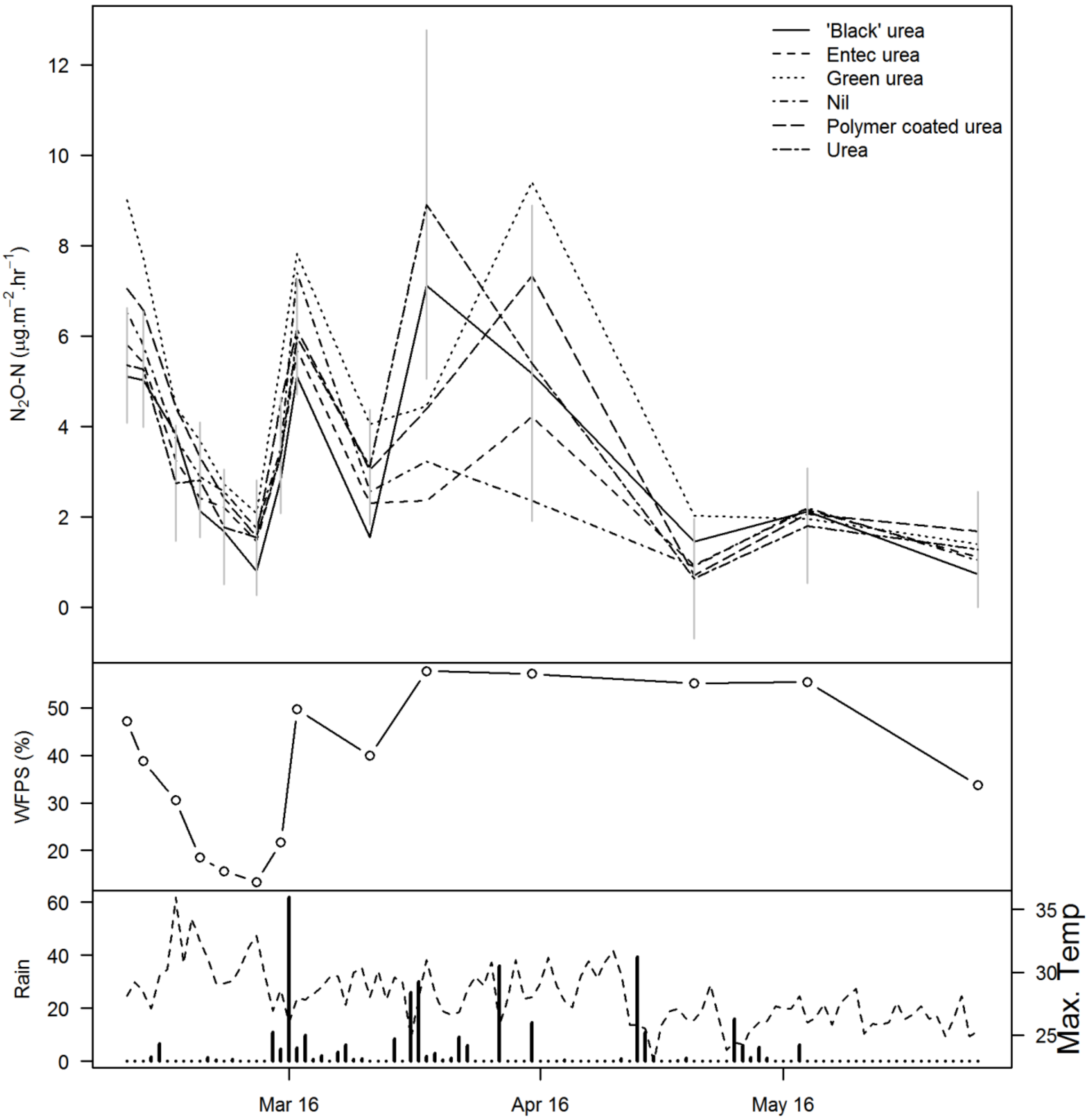


Figure 12. **Nitrous oxide emissions (observations) under seven N fertiliser treatments at Woolley's property in 2015-16. The second panel depicts Water Filled Pore Space (WFPS) in the soil. The lower panel shows weather observations.**

Outcome 3: Increased carbon stored in soil

Trials at Rice Research Australia commercial farm and Mauger's farm investigated soil carbon dynamics with novel stubble management practices compared to the standard practices of burning stubble or baling and removing stubble. At the Rice Research Australia commercial farm trial, there was no significant difference in soil total carbon or carbon fractions among treatments after one season (data not shown); however, after three consecutive seasons of biochar and compost addition soil total carbon was significantly higher in the biochar plots than the stubble removed plots in the 0-100 mm horizon (Table 12). This appeared to be mainly a result of increases in the recalcitrant organic carbon fraction, where biochar plots had a mean of 0.36 % compared to 0.30 % in stubble removed plots, but the increase was only significant at P = 0.08 (data not shown). There were no significant differences in soil total carbon or carbon fractions among stubble management treatments in the 100-300 mm horizon after three seasons.

Table 12. Changes in soil total carbon and carbon fractions in the 0-100 mm and 100-300 mm horizons at the Rice Research Australia commercial farm stubble management trial after three consecutive seasons of biochar and compost addition. Means within a column for each soil horizon that do not share a common letter are significantly different at P = 0.05.

Stubble treatment	Total carbon (%)	Total Organic Carbon (TOC) (%)	Particulate Organic Carbon (POC) (%)	Char (ROC) (%)	Humus (HUM) (%)
0-100 mm					
Stubble removed	1.5 a				
Stubble removed + compost	1.7 b	ns*	ns*	ns*	ns*
Stubble removed + biochar	2.0 c				
mean		1.6	0.35	0.33	1.1
100-300 mm					
Stubble removed					
Stubble removed + compost		ns*	ns*	ns*	ns*
Stubble removed + biochar					
mean	0.64	0.82	0.08	0.17	0.61

*ns denotes no significant difference among means at P = 0.05

The trial at Mauger's property examined changes in soil carbon fractions over a single season when stubble was either incorporated into the soil or returned as biochar vs stubble being burnt or baled and removed. Stubble treatment had no significant (at P = 0.5) effect on soil total carbon (mean = 2.1 %), total organic carbon (mean = 2.0 %), particulate organic carbon (mean = 0.44 %), recalcitrant organic carbon (mean = 0.49 %) or humus carbon (mean = 1.14 %) in the 0-100 mm horizon. The same lack of effect was observed in the 100-300 mm horizon (data not shown). These results concur with the results of the Rice Research Australia commercial farm stubble trial where no significant effect of stubble treatment was observed after one season. It appears that any effects of stubble treatment on soil carbon and soil carbon fractions only become apparent is treatments are applied continually over a number of seasons.

Dissemination of results

The results for the three outcomes discussed above (Reduced methane emissions from flooded rice systems; Reduced nitrous oxide emissions from subtropical rice soils; Increased carbon stored in soil) were shared with farmers, advisors and industry groups through a variety of presentations at field days, industry research updates and newsletters as per agreed milestones and outputs. In total, the findings of the project were disseminated to more than 150 farm businesses.

Implications and Recommendations

Explain the significance of these findings for policy makers and the Australian agricultural industry.

The most significant finding from the project was that drill sowing and delayed permanent water systems in the temperate Australian rice industry more than halve the in-crop methane emissions and do not increase nitrous oxide emissions. Given that drill sowing reduces water use and does not negatively affect grain yields, drill sowing represents a practical option for rice farmers to mitigate methane emissions with no negative impact on crop gross margins.

Another key finding from the project was that pyrolysing stubble and re-applying it to soils does not appear to increase methane emissions from rice crops, although the increased nitrous oxide emissions when biochar was added suggest that nitrogen recommendations need to be modified. The addition of pyrolysed rice stubble also resulted in significant increases in soil carbon when applied over three consecutive seasons. Pyrolysis of rice stubble appears to be a possible means to reduce stubble burning and the loss of nutrients and carbon from rice soils in the MIA without increasing greenhouse gas emissions; however, a full life cycle analysis needs to be undertaken to determine if such a practice is economically viable.

Finally, current commercially available N fertilisers containing nitrification or urease inhibitors do not show any consistent reduction in cumulative seasonal nitrous oxide emissions in rice crops grown in the subtropics. Given that these products have been shown to reduce nitrous oxide emissions by on average 40% elsewhere in the world, steps need to be taken to resolve why they had minimal impact in the warm, humid wet subtropical region of northern NSW and efforts made to develop products that can lower nitrous oxide emissions in these environments.

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AgriFutures™ Rice

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by Neil Bull & Terry Rose

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